Boiling Heat Transfer: Convection Controlled by Nucleation

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Abstract

Due to the peculiar way of evolution of boiling heat transfer research, a model "theater of director" (MTD), pumping effect of growing bubble (PEGB) and MTD-based universal correlation (UC) remain beyond the attention of researchers for more than half a century. In parallel, there are periodic fundamental events, demonstrating the irrationality of such indifference. Since the 1980s, not having found a way to enhance boiling heat transfer, other than that uncovered by the MTD-UC, high-performance boiling surfaces are being developed by artificially increasing effective radius (ER) of nucleation centers (bypassing the reference to the relevant theoretical basis). In 2009, an independent review declares transient conduction and microconvection as the dominant boiling heat transfer mechanism, not knowing that this is just the PEGB. In 2014–2017, the real versatility and accuracy of the UC is confirmed by independent studies, which involve extensive databases on the pool and flow boiling (with some interpretation problems). Assessing the current status of the study, the chapter emphasizes the complete fiasco of traditionally adopted approaches, models and theories, led to the dominance of purely empirical relationships written in a dimensionless form. Heat transfer research community is invited to gain will and rid of the heavy burden of the past.

Keywords: boiling, nucleation, heat transfer, pumping effect, effective radius, correlation

1. Introduction

Importance of boiling heat transfer research is determined by the implementation of this process in the most energy-intense components of technical systems in nuclear and thermal power, space, aviation, cryogenics, refrigeration, chemical and other technologies. The complexity of the boiling phenomenon is due to the combination of turbulence and phase conversion with intricate feedbacks generating complex irregular dissipative structure with various thermo-hydrodynamic effects.

Eventually, all this translates into the exceptional peculiarities of this type of convective heat transfer. Because of this and some other reasons a great number of studies carried out for almost a century after the classic works of Max Jacob and his colleagues [1] have not yet led to generally recognized theory of boiling heat transfer, still remaining as the central unsolved problem of heat transfer theory.

By today's view, boiling heat transfer research has produced a huge agglomeration of experimental facts, analytical and numerical models, and countless helpless correlations, not unified by any single ideology. This agglomeration not only rendered meaningless numerous concrete real scientific achievements but also buried the real boiling fundamentals, the pumping effect of growing bubble (PEGB), the model theater of director (MTD), the universal correlation (UC) capable of serving as a robust framework for solving the problem as a whole.

Of course, understanding of revolutionary new model requires some time. However, half a century of delay with confirmation of the validity of the UC, which requires simple arithmetic calculations, cannot be explained in terms of conventional scientific practice. In this regard, one fact deserves attention. A very short abstract of the most accessible at that time international publication of the MTD-UC [2] claims to submit the UC of developed boiling heat transfer covering all groups of liquids including liquid metals without matching different constants and powers to different surface-liquid combinations.

Boiling heat transfer researchers simply had to check the above claim for a scientific breakthrough. Despite this, during the past almost 40 years, except for self-citations, the article has never been cited by any researcher. The author's systematic calls for a change in irrelevant approaches to the MTD-UC also prove futile. Obviously, such a situation is not an indicator of the overall focus on the effective solution of the boiling problem. Moreover, this clearly indicates a complete suppression of fair scientific debate and competition in the field.

Later, taking into account the above features of the current situation, we pay particular attention to comprehensive examination of the rare belated episodes of de facto validation of the boiling fundamentals by independent studies.

2. The MTD as an alternative to traditional approaches

The uniqueness of boiling heat transfer manifests itself in the independence of the intensity of heat transfer in developed boiling mode from the macro-hydrodynamic parameters of the two-phase medium. Drastic changes of these parameters with a change in the acceleration of gravity by several orders or significant supercooling of the bulk liquid practically do not affect the superheat of the heating surface relative to the saturation temperature.

These features of the boiling phenomenon, paradoxical from the standpoint of traditional concepts of convective heat transfer, were fully uncovered only in the 1960s. Before this, the classics of the theory of boiling heat transfer Jakob [1], Kruzhilin [3], Rohsenow [4], and other researchers have had to develop boiling heat transfer theory based on a traditional approach of convective heat transfer theory connecting heat transfer to the intensity of certain cooling mechanism or combination of certain cooling mechanisms (the MTA).

In parallel, based on an analysis of just the newly uncovered features, in the same 1960s, an alternative model (the MTD) was proposed that highlights the governing role of nucleation in the developed boiling heat transfer [2, 5–11]. Ultimately, the MTD led to adequate description of a vast array of experimental data on developed boiling heat transfer, outlined an effective way to enhance heat transfer successfully implemented since the 1980s in the form of high-performance boiling surfaces.

The principal difference between the MTD and MTA is particularly clearly manifested when comparing the characteristic lengths of the process. In the case of the MTA, this is the parameter of the macro-hydrodynamics of two-phase medium (e.g., the bubble detachment diameter or the internal diameter of the channel), the multiple change of which practically does not affect the superheat of the heating surface relative to the saturation temperature.

In the case of the MTD, this is the average effective radius (ER) of nucleation centers, which just reflects controlling role of nucleation. This linear scale not only contributes to universal description of heat transfer in developed boiling mode regardless of the geometry of the medium and the type of a boiling liquid but also serves as a tool for heat transfer enhancement. The ratio of two different scales (of the order of 10^5–10^6) would seem to emphasize the qualitative gap between the MTD and MTA.

2.1. Pumping effect of growing bubble

A special role in the prediction of the PEGB and development of the MTD was played by the discovery of local temperature pulsations of heating surface [12]. Establishment of coincidence of main cooling effect with onset of bubble growth (**Figure 1**, points **a** and **c**) has led to breakthrough in understanding of boiling phenomenon. The particular surprise was the disclosure of the secondary role of heat removal during the detachment of the bubble and its replacement by liquid mass that was considered as the main cooling effect according to the ideas existing at that time.

Simultaneously, a serious problem arose in terms of reconciling the identified pattern with a fairly firmly established fact of the predominant role of heat removal by the liquid phase, which led to the tendency of unjustified exaggeration of the role of the microlayer evaporation (MLE) [12]. On a qualitative level, a complete clarification of this problem was achieved by predicting the PEGB [5, 6].

The PEGB represents acceleration by vapor bubble of liquid jet at the initial stage of growth normal to the heating surface, accompanied by microcirculation in the boundary layer (**Figure 2**). According to the model [5–7], the PEGB is caused by the abrupt variability of the transverse momentum transfer by evaporation along the surface of the bubble, say, by the abrupt variability of the reactive force applied to the surface of the growing bubble. Let us look at the effect in combination with a typical cycle of local temperature pulsation.

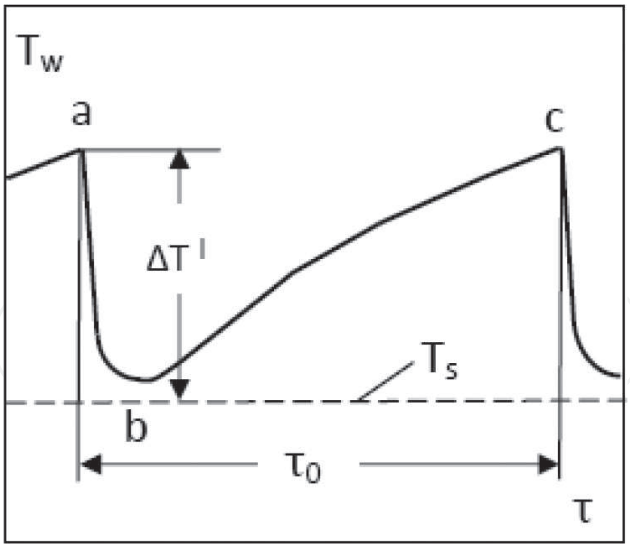

Figure 1. Typical cycle of local temperature pulsation of heating surface [12]: T_w—local superheat of heating surface; T_s—temperature of saturation; ΔT′—maximum superheat; τ—time; τ_o—duration of the pulsation cycle.

After point b (**Figure 1**), the convective cooling effect is greatly reduced and the wall and adjacent liquid begin to warm up, mainly by transient conduction. At point c, wall overheating becomes sufficient to start the growth of the next bubble. The PEGB is again launched with another powerful short-term cooling effect, similar to sections a–b. In terms of collecting heat of the overheated liquid and transporting it first to the growing bubble and then to bulk liquid, the scheme seems almost ideal.

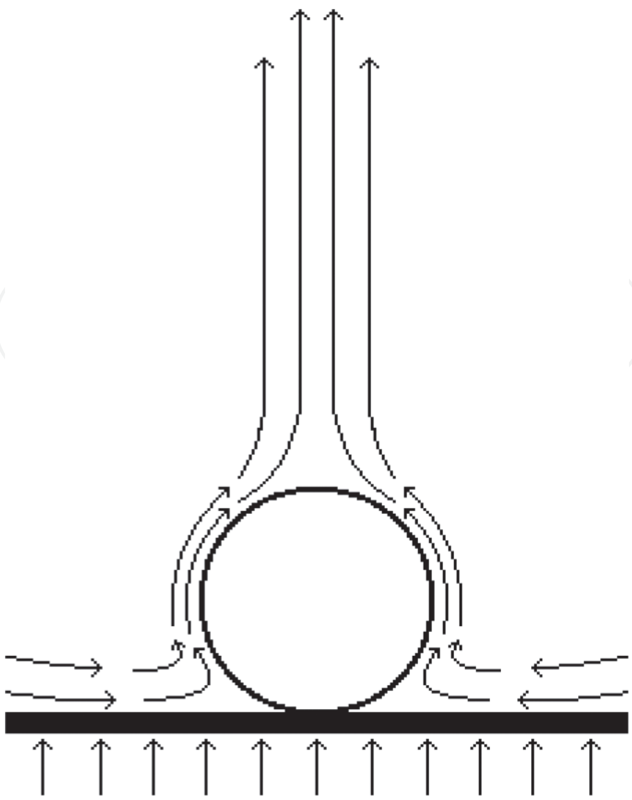

Figure 2. A model of pumping effect of growing bubble (PEGB) [5].

Intensity of the PEGB strongly depends on initial superheat of boiling surface. Therefore PEGB is much more intensive at relatively low pressures, small-sized nucleation sites and high surface tension (e.g. in liquid metals). "Switched on" simultaneously with the onset of bubble growth, the PEGB quickly reduces initial gradient of temperature due to that it arises and "cuts off" itself even if a bubble still remains on the wall. By the way, according to considerations [13], just this feature leads to quite impressive phenomenon of a bubble detachment against gravity force [14].

As a whole, the PEGB reconciles character of local temperature pulsation with prevailing role of liquid phase convection in the majority of boiling processes opening thereby a new line of attack on the boiling problem.

Over the past decades a number of experimental proofs were obtained directly confirmed existence and importance of the PEGB. Unfortunately, accidental rather strong manifestations of the effect with jet velocities in the range 1–5 m/s observed in some yearly experiments were left without proper interpretation [15, 16], for example, speeded-up liquid jet flow (5 m/s) penetrating through full-grown large preceding vapor bubble (**Figure 3**), the frame of which was published without any comment [15].

Real steps toward study of the PEGB during boiling on thin wires firstly were made in the works [17, 18]. Rather powerful manifestations of the PEGB were observed and recorded, including phenomenon of vapor bubble departure against gravity field. Diverse dynamical effects were studied including bubble-specific motion on micro-wires. Non-gravity nature of the observed phenomena was confirmed. Numerical model of bubble motion and jet flows through subcooled boiling on micro-wires was developed. At the same time, the interpretation of received data and evaluation of the role of the Marangoni effect in the PEGB became a subject of discussion [19, 20].

Very powerful manifestation of the PEGB is observed during laser drilling of nickel and copper [21]. The fixed velocities of the ejected liquid jets achieve 100–150 m/s. Though the authors link

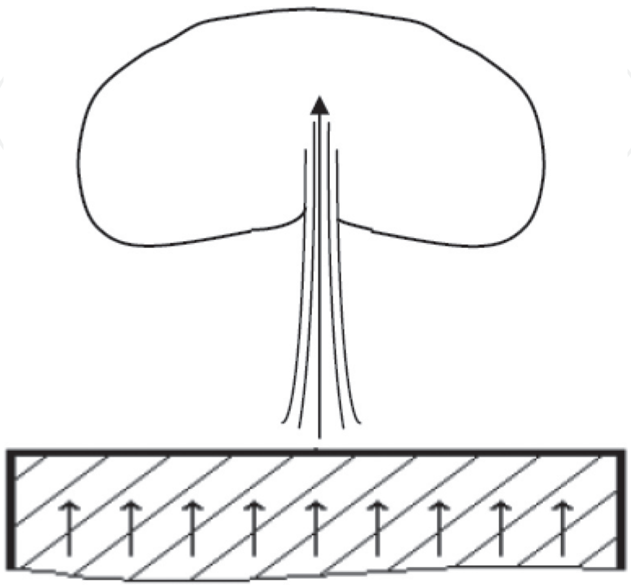

Figure 3. Liquid jet flow (5 m/s) penetrating through full-grown large preceding vapor bubble [15].

the effect to vapor bubble nucleation (to say, to the PEGB), this specific phenomenon requires further investigation. Tangible episodic manifestations of the PEGB were recorded also during boiling on down-facing heating surface [22].

The specific case of jet flow, containing the chain of micro-bubbles, was observed during experiments on subcooled boiling on micro-wires in micro-gravity [23]. Recorded velocities of micro-bubble jets (4–14 mm/s) are at 2–3 order lower than the jet velocities observed in aforementioned experiments (1–5 m/s and more). It may turn that the observed micro-bubble jet is the end result of numerous "micro-launches" of the PEGB, each of which detaches from the heating surface a single micro-bubble by the scheme [13].

In general, the studies are episodic. Especially when compared with the relatively minor MLE the study of which was the subject of numerous studies. It still is not examined the dependence of the effect on the properties of boiling medium and heating surface, heat flux, saturation pressure, and subcooling, the orientation of heating surface in the space. The most important in terms of understanding of the phenomenon relationships between the PEGB and local temperature pulsations are not investigated at all. In this connection, it still remains outside the field of view of researchers' specific type of thermal fatigue associated with cyclic thermal stresses generated by the PEGB [24].

The results of modern comparative studies of different boiling heat transfer mechanisms are also worthy of attention. In this context, it is of particular importance the actual confirmation of the status of the PEGB as the main cooling mechanism during boiling heat transfer by comprehensive review [25].

The review covers numerous experimental works, analytical and numerical studies. Having analyzed the experimental data obtained through various modern methods, such as micro-heater array, micro-heat flux sensors, and liquid crystal techniques, and comparing them with the results of numerical and analytical studies, the author makes an unambiguous conclusion about the impossibility to explain the observed pattern of heat inflow in a bubble during boiling by known to the author of the review heat transfer mechanisms, including MLE and contact line heat transfer.

The main outcome of the review is the fundamental conclusion about dominant role of heat transfer by liquid phase through "transient conduction and micro-convection." It also is concluded that "none of the proposed bubble heat transfer models described in the Introduction are consistent with the experimentally observed heat transfer signatures."

As follows from **Figure 2**, given in [25], characteristic of the basic heat transfer mechanism really is a brief description of the PEGB. The PEGB is an almost ideal mechanism for collecting heat accumulated by transient conduction in liquid boundary layer with its further transport through micro-convection to the almost whole surface of the bubble and then to bulk liquid.

Unfortunately, despite rather wide international publishing [2, 6, 7, 9–11], the PEGB turned to be unknown to the author of the review [25]. It also turned to be unknown an approximate analytical solution [2, 8, 13] just considering the combination of the transient conduction and microcirculation. These facts prevented the review to identify the real beneficiary of the study.

At the same time, the conclusion about the main role of "transient conduction and micro-convection" should not be taken as all-embracing. Studies of cooling mechanisms still do not adequately cover such processes as boiling at very high pressures or small gravitational accelerations in which the MLE can outperform the PEGB in importance.

In terms of refinement of the model [5–7], it deserves a serious attention the potential dynamic consequences of the rapid transition from one stable capillary state to another at the stage of nucleation (**Figure 4**), similar to the dynamic effect of "jumping droplets" [26].

In position 1, the nucleus meniscus still holds the wetting angle θ with the inner surface of the conical cavity, but the radius is almost equal to the radius of the mouth. During the nucleation (during overcoming the mouth), rapid transition of the same wetting angle θ to the base heating surface (position 2) occurs with associated dynamic effects, similar to the coalescence of the droplets. The transition is accompanied by change in the surface energy, corresponding thermal effect, and expansion work.

In fact, the emerging bubble is a capillary micro-heat engine that pushes the fluid from the heating surface, to say, promotes the PEGB. The relevant task is to determine the contribution of this micro-heat engine in the overall effect.

2.2. The MTD: heat transfer controlled by nucleation

The MTD is based on the fundamental fact of independence of heating surface superheat relative to the saturation temperature in developed boiling mode not only on the individual contributions of various cooling mechanisms but even on the number and composition of

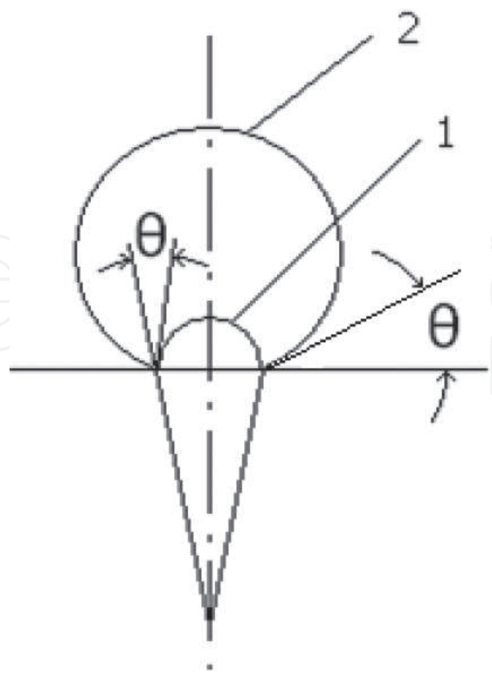

Figure 4. The scheme of the nucleation.

these mechanisms. Another important basic fact is the launch of the main cooling mechanisms by the onset of bubble growth and the short duration of their action.

In boiling of saturated liquid, one can distinguish four cooling mechanisms (**Figure 5**). Among them only the MLE [12] is linked to immediate evaporation on the boiling surface (**Figure 5a**). Other three mechanisms, bubbling [1] (**Figure 5b**), the PEGB or jet-like (**Figure 5c**) and the micro-membrane pumping (MMP) [27] (**Figure 5f**) are linked to liquid phase convection. With another approach, the number of cooling mechanisms could be greater. For instance, cooling mechanisms such as through pushing the liquid by growing bubble, through displacement of overheated liquid layer, or through drift liquid current subsequent to detached bubble sometimes are thought to be separate mechanisms. Here, these mechanisms are seen as the stages of the bubbling mechanism.

Less well-known MMP is a specific cooling mechanism due to permanent vibration of nuclei in potential centers synchronously with the local temperature pulsation of the heating surface. As the temperature increases, a nucleus surface ("micro-membrane") expands to critical profile, stops expanding when the nearest nuclei launches the PEGB with relevant cooling effect, and returns to the previous position with the temperature drop.

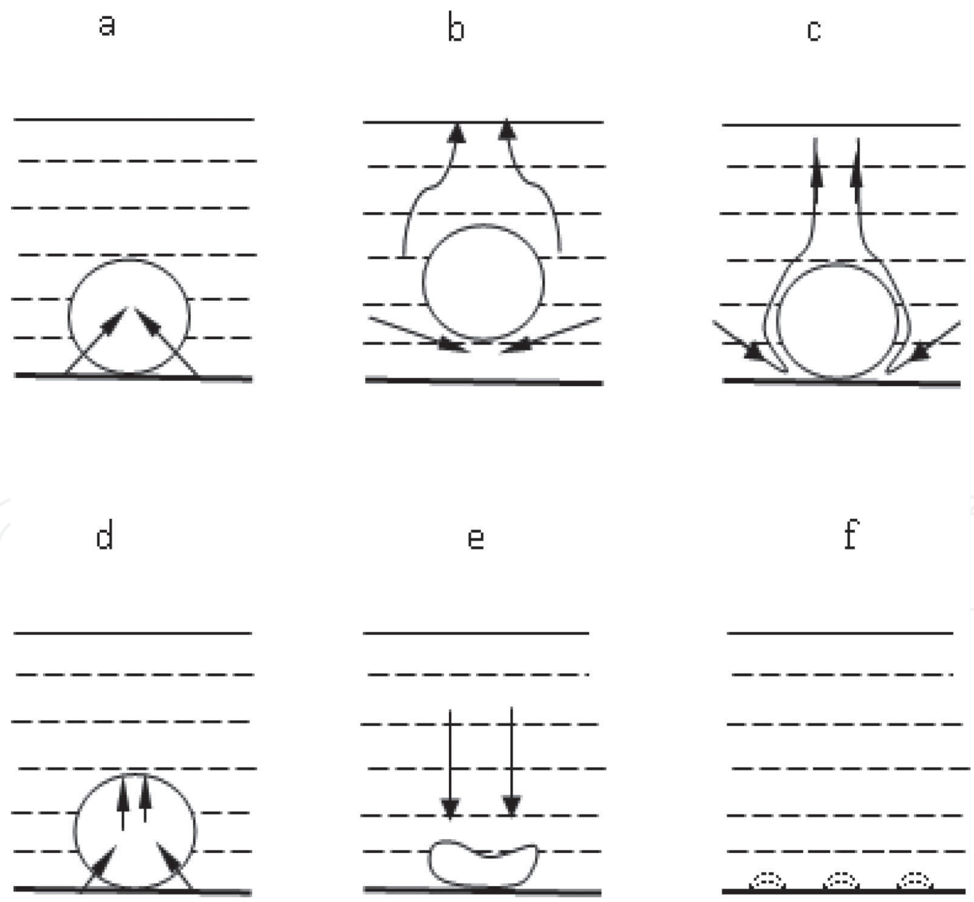

Figure 5. Schematics of cooling mechanisms: a—MLE; b—bubbling; c—PEGB; d—heat pipe-like; e—BCD; f—MMP.

Subcooling puts in operation two additional cooling mechanisms: heat pipe like (evaporation-condensation) [28] (**Figure 5d**), being an extra version of MLE, and bubble collapse-driven mechanism (BCD) (quasi-cavitational) [29] (**Figure 5e**) associated with the collapse of a bubble on the surface under the influence of influx of highly subcooled liquid.

As you can see, the main cooling mechanism (the PEGB) and its main assistants, the MLE, possibly the MMP and the BCD in the case of subcooled liquid, are all launched by the onset of bubble growth and have a short-term effect.

Data showing a virtually zero effect of a significant redistribution of the total heat flux between the various cooling mechanisms on the developed boiling heat transfer law are analyzed in the reviews [13, 30]. Here, we can confine ourselves to an impressive example of the BCD [29], which is absent altogether in the boiling of a saturated liquid and is quite intense in the case of surface boiling of a highly subcooled liquid. Despite this, these two processes reproduce the same developed boiling heat transfer curve.

Finally, based on these features of developed boiling, the MTD assumes control of the superheat by nucleation through multiple triggering short-run cooling actions of different cooling mechanisms. It also is assumed that onset of a bubble growth takes place at the instant the average temperature of the meniscus of critical size overcomes the temperature of thermodynamic equilibrium in the system nucleus-liquid-center.

It should also be clarified that the introduction of the MTD does not necessarily mean the inapplicability of the MTA in the analysis of developed boiling heat transfer, in general. We are talking only about extremely low efficiency of the latter in this particular case.

Let us take as an example an imaginary experiment with the process of developed boiling at a given heat flux. Changing within broad limits the acceleration of gravity and subcooling, we can set thousands of regimes of developed boiling with different compositions of cooling mechanisms and their various contributions to the overall heat transfer.

An accurate calculation of each such regime through the MTA is still an insoluble task. At the same time, when numerical models achieve such perfection, we will face a very peculiar situation: it turns out that thousands of complicated calculations result in the same overheating of the boiling surface relative to the saturation temperature. As for the MTD, it simply aims to identify the same overheating through the mechanism that sets it.

The MTD incorporates one-parameter model of boiling surface consisting of unlimited number of identical stable nucleation centers with the same ER characterized by unchangeable level of the superheat, triggering the growth of the first and following bubbles. The role of such a center may be played by conical recess with apex angle β satisfying the condition:

$$\frac{1}{2}\beta < \theta < 90^0 \tag{1}$$

The minimum curvature radius of the nucleus surface ρ_0 (the ER) in similar center is equal to the radius of the mouth [31].

The coverage area of the operating nucleation center is determined in a self-organized manner by the ability of the initially activated nucleation center to prevent by own cooling effect the activation of neighboring potential centers with the same ρ_0. If such zone of influence is reduced (e.g., with increasing heat flux), the former periphery overheats, and an additional center or centers with the same ER turn into operation there. Simultaneously, the new periphery is formed closer to the center. Of course, the process can also proceed in the reverse order. In such a framework, heating surface affects heat transfer by a single parameter, the ER.

Next, in the first place, within the framework of the MTD, an approximate analytical solution is made for the area adjacent to nucleation center [2, 8, 13]. The analysis approximates local temperature variation by the curve presupposing instantaneous drop in the wall temperature down to the saturation temperature at the onset of bubble growth (instantaneous start-up and shut-down of very intensive heat removal, e.g., by microcirculation (the PEGB) and immediate evaporation (the MLE)) and further warming-up of the wall through transient conduction up to the moment of onset of the next bubble growth (**Figure 6**).

The superheat ΔT_{eq} necessary for bubble growth onset, should be achieved at the meniscus of the nucleus in average. As critical nucleus is in the zone of temperature gradient, concomitant heating surface superheat $\Delta T'$ is much above ΔT_{eq}. Corresponding unsteady-state process is considered as warming-up of initially isothermal liquid semi-infinite space (with initial temperature equal to T_s) through transient heat conduction at suddenly posed boundary condition $q = Const$. The superheat ΔT_{eq} is determined by the relationship [18]:

$$\Delta T_{eq} = \frac{2\sigma T_s}{r \rho_0 \rho_g}, \quad (2)$$

where σ is the surface tension, r is the heat of evaporation, and ρ_g is the density of vapor.

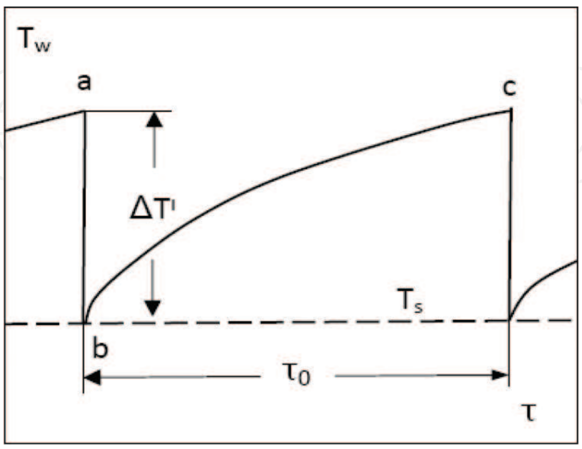

Figure 6. The first approximation.

On the basis of the general solution of the problem [32], the equations are obtained for the Nusselt number (Nu) and the rise time of the heating surface temperature (τ^*):

$$Nu = \frac{3\sqrt{\pi}}{2}\frac{\rho_0}{2\sqrt{\alpha\tau^*}}, \tag{3}$$

$$\frac{\rho_0}{2\sqrt{a\,\tau^*}}\frac{1}{ierfc\frac{\rho_0}{2\sqrt{a\,\tau^*}}} = \frac{K}{2}, \tag{4}$$

where h is the heat transfer coefficient (HTC), k is the thermal conductivity of the liquid phase, a is the thermal diffusivity of the liquid phase, and q is the heat flux.

$$Nu = \frac{h\rho_0}{k} \tag{5}$$

$$K = \frac{q\,\rho_0^2\,r\,\rho_g}{\sigma\,kT_s} \tag{6}$$

According to relevant comparison [2, 13], the analytical solution (3)–(4) predicts the order of HTC during boiling of nitrogen, water and sodium at atmospheric pressure. Taking in account the great difference between the liquids, such an outcome of approximate analysis still can be considered as a serious support of validity of the MTD. Important outcome of the solution is disclosure of the number K and characteristic length—the ER.

The theory is further refined through introducing some qualitative considerations of the periphery of the action zone of the center, given that it makes major contribution to the average superheat. The prolongation of liquid micro-convection by inertia after the termination of the action of PEGB also is taken into account. Based on some qualitative considerations, in addition to K, following modified Reynolds number is introduced:

$$\mathrm{Re}_{*,s} = \frac{C_p\,\sigma\rho\,T_s}{r^{3/2}\,\rho_g^2\,\nu} \tag{7}$$

where C_p is the heat capacity of the liquid, ρ is the density of the liquid, and ν is the kinematic viscosity of the liquid.

Finally the following correlation, Shekriladze and Ratiani, for developed boiling HTC is developed [2, 8–11, 13]:

$$Nu = 0.91 \cdot 10^{-2}\,K^{0.7}\,\mathrm{Re}_*^{\;0.25}, \tag{8}$$

An important outcome of the Eq. (8) is the disclosure of rather strong dependence of HTC on the characteristic length $(h\sim\rho_0^{0.4})$. Just this dependence marked the basic direction of boiling heat transfer enhancement by creating on the heating surface nucleation centers with large ER. With the exception of a misprint in article [8] (the coefficient of 0.88×10^{-2} instead of 1.22×10^{-2} in equation (10)), the presence in the part of publications of the other constant in the same Eq. (8) (1.22×10^{-2} instead of 0.91×10^{-2}) is due to the different records of Re^*: through specific work of expansion or through heat of evaporation (taking into account that $P(v_g\text{-}v) \approx 0.1r$ (P is the absolute pressure, v_g is the specific volume of the vapor, and v is the specific volume of the liquid)).

2.3. The ER, correlation of experimental data, and heat transfer enhancement

Disclosed by solutions (3)-(4), characteristic length especially clearly showed the basis of universality of the UC. Just the fact of the generation of control impulses by the nuclei of about 10 μm in size create the basis for the independence of wall superheat in the developed boiling mode from macro-hydrodynamics of two-phase medium, intensity of mass acceleration, the geometry and sizes of the heating surface, including microchannels. All of these parameters can affect the range of heat fluxes (beginning and end) of the developed boiling mode but not heat transfer law within the mode.

By the way, longstanding disregard of the MTD-UC was accompanied by a remarkable phenomenon: the concept and the term "characteristic length" left the scientific publications on boiling heat transfer for decades. The importance of knowledge or experimental determination of this parameter has ceased to be discussed at all.

As a result, an opportunity has been lost to stop the ordinary experimental practice to study boiling heat transfer without measuring the ER, a single parameter of the heating surface greatly affecting the HTC. If you try to invent an analogy to this situation, we could talk about the experiment on the hydrodynamics of the channel flow without measuring the cross-sectional dimensions of the channel.

The possibility of translating virtually all known correlations into the category of empirical relationships written in dimensionless form (due to the lack of the real characteristic length in them) was also missed.

In terms of the confirmation of the validity of the UC, it becomes particularly important a very few experimental studies including data on the ER and covering greatly differing liquids (sodium [33], water [34], refrigerants [35]) on the heating surfaces with highly different ER. Correlation of these data by the UC, borrowed from [2, 13, 36], is presented in **Figure 7**.

The correlation represents a fundamental confirmation of the validity of the MTD-UC and the role of the ER as the characteristic length. It is also obvious that the data presented in **Figure 7** cannot be described in a unified manner by the correlations that do not contain the ER (i.e., by all known correlations, other than UC). Incidentally, during boiling of sodium at $\rho_0 = 50\ \mu m$, HTC is 2.5 times higher than on commercial surface, other conditions are the same. The same enhancement factor for the refrigerants is 3.1.

Universal character of the Eq. (8), also can be demonstrated by the correlation borrowed from [22] (**Figure 8**) including, together with experimental data on pool boiling of Cesium and Hydrogen, the data on flow boiling of R11 and HCFC1 in a narrow passage and flow boiling of subcooled water in a microchannel.

To a certain extent, the problem of poor knowledge of boiling surfaces is also mitigated by the use in many experiments of commercial heating surfaces (mainly rolled pipes), which is characterized by the ER equal to 5 μm based on some indirect evidences [2, 8–11, 13, 34].

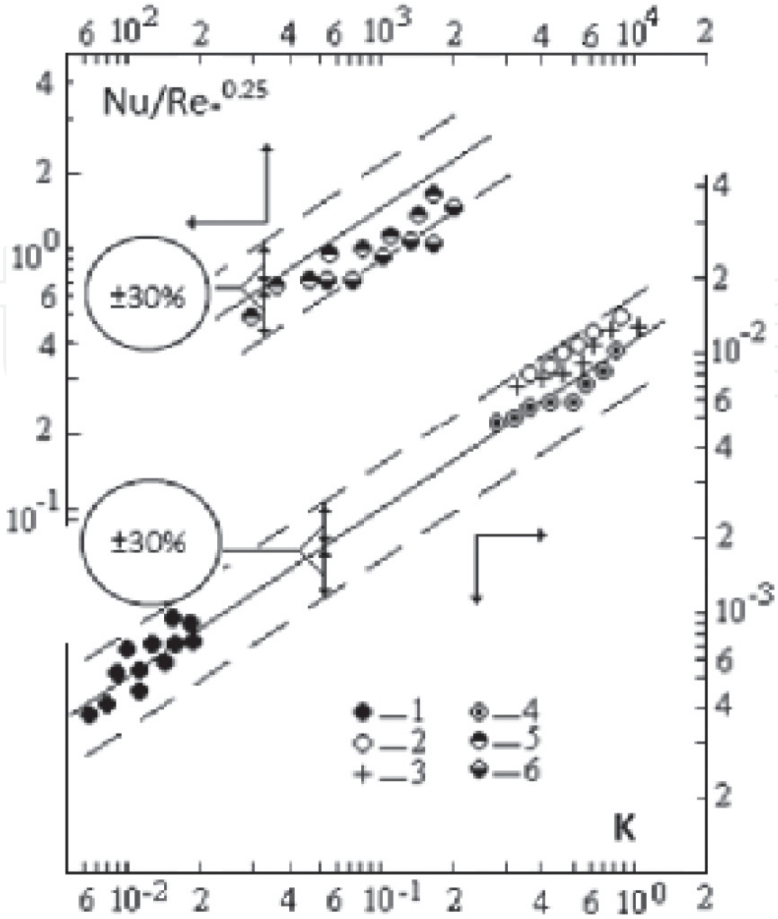

Figure 7. Comparison of Eq. (8) with experimental data on developed boiling on the surfaces with the known values of the ER: 1—sodium [33], $\rho_0 = 50\ \mu m$; 2–4—water [34], $\rho_0 = 5\ \mu m$; 5—R 12 [35], $\rho_0 = 86\ \mu m$; 6—R 22 [35], $\rho_0 = 86\ \mu m$; solid lines—Eq. (8).

Relying on a similar assessment of commercial surfaces, the validity of Eq. (8) is confirmed by a wide database on developed pool boiling of all groups of liquids including liquid metals and cryogens without matching different constants and powers to different surface-liquid combinations. The correlation covers the data on boiling of water, ammonia, ethyl alcohol, benzene, biphenyl, ethane, ethylene, R11, R12, R22, R113, R134a, R142, HCFC123, Na, K, Cs, Hg, CO, NO, BF_3, N, Ne, and H [2, 8–11, 13, 33].

Now let us look at the problem of boiling heat transfer enhancement. As mentioned, the MTD has determined the basic principle of boiling heat transfer enhancement: providing plenty of stable nucleation sites with large ER. At the same time, the UC has predicted the highest achievable enhancement factor ($h \sim \rho_0^{0.4}$). Over the past decades, enhanced boiling surfaces have been developed in direct using this basic principle. Outstanding achievements of this line of R&D have led to substantial progress in relevant technologies.

However, all the above circumstances have not prevented complete silencing of the MTD-UC-ER. The role of the boiling fundamentals turned out to be hidden by a rather simple way: the important issues to specify the scientific bases of development of the enhanced boiling surfaces and analyze the results in the same basic framework, they are generally avoided in the publications. A recent survey [40] may serve as an example of such an approach.

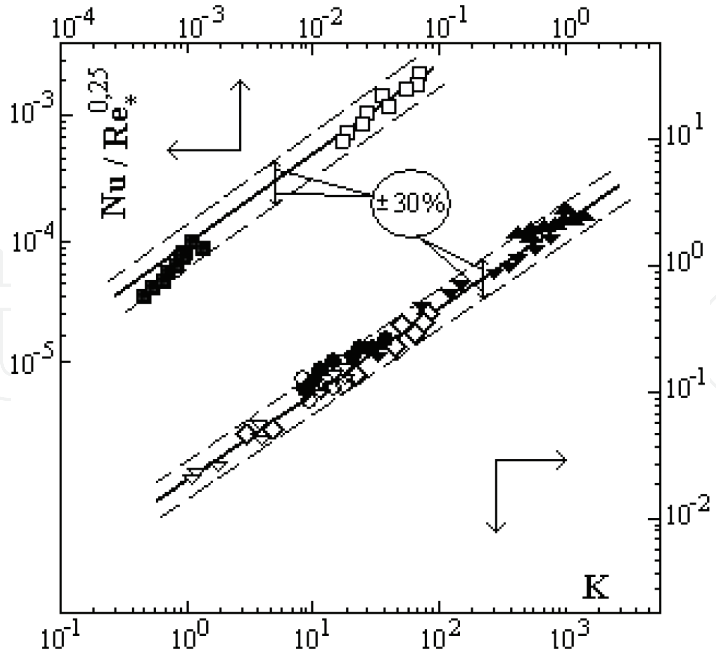

Figure 8. Correlation of experimental data on pool boiling HTC of cesium [36]: ■—1.82·10³ Pa; □—1.58·10³ Pa; pool boiling of hydrogen [37]: ∇—0.82·10⁵ Pa;▼—5.16·10⁵ Pa; ▲—8.50·10⁵ Pa; flow boiling in narrow passage [38]: ●—R11, 1.0·10⁵ Pa; o—HCFC123, 1.0·10⁵ Pa; flow boiling of subcooled water in a microchannel [39]: ◊—1.0·10⁵ Pa; solid lines—Eq. (8).

Finally, we should also address the issue of the limitations of the MTD. As it follows from the above correlations, developed boiling represents the most conservative basic regime of boiling heat transfer characterized by the dependence of HTC on restricted number of influencing factors. According to Eq. (8), together with the physical parameters of boiling area, developed boiling HTC depends only on two "external" factors—heat flux and the ER. As it follows from relevant analysis, such a conservatism of developed boiling heat transfer can be linked to the existence of a great (practically unlimited) number of stable nucleation sites with roughly uniform effective radii, short duration of each action of any cooling mechanism and prevailing contribution of heat removal by liquid phase convection.

According to the multi-factoring concept (MFC) [41], any failure to meet these conditions results in essential transformation of heat transfer regularities up to drastic increase of the number of influencing HTC factors. For instance, depending on concrete conditions, the circle of influencing HTC factors may be widened by the parameters of inter-phase hydrodynamics, intensity of body force, contact angle, subcooling, sizes, form, orientation, and thermal characteristics of the heating surface, micro-geometry, and distribution of nucleation sites, and prehistory of the process. Besides, multi-factoring may be accompanied by "passing on the baton" from the MTD to the MTA. As it follows from qualitative consideration, there can be distinguished two main types of multi-factoring:

- The first— connected with onset of dependence of effective radius (ER) on a degree of penetration of liquid into nucleation site (wetting-dependent multi-factoring (WDM)),
- The second—connected with transition to prolonged duration or uninterrupted regime of action of any intensive cooling mechanism (duration-dependent multi-factoring (DDM)).

The MFC opens up a promising path to the description of the observed in experiments diversity of boiling heat transfer curves, including boiling hysteresis (for more details, see [13, 22, 41]).

Finally, another very important aspect of the boiling heat transfer research should be noted. Due to the complete neglect of the above boiling fundamentals, a very important direction of boiling heat transfer research, numerical modeling, has lost consistent bases [42]. As a result, the direction still has not reached the level to be taken into account when analyzing the existing experimental data bases [43, 44].

3. Hard steps to recognition

The results of the first independent comparison of UC with experimental data were published only on the eve of the 50th anniversary of the publication of the correlation itself [43]. Despite the problems, with some applied methodological approaches and interpretations, the results of the comparison allow us to draw some important conclusions.

Using quite broad experimental database on heat transfer during pool boiling of 55 non-metallic liquids on copper heating surfaces, the authors identified the nine “most advanced” equations among tens and even hundreds of correlations published for more than half a century. Further, comparing these nine equations, they have identified three equations with the “low level” of the mean relative deviation (MRD): the equation of Gorenflo and Kenning updated in 2010 (the MRD 9.5%), the UC (10.8%), and the equation of Stephan and Preusser (12.1%) surpassing other equations in accuracy.

Unfortunately, in [43], important results of the comparison were not supported additionally by their comprehensive analysis. A thorough criticism of the corresponding part of the work was given in [45].

Here, we only note that the significance of the study would be greatly increased by clarifying the potentially appreciably higher accuracy of the UC.

The matter is that the UC participates in competition with other equations on unequal conditions. On the one hand, the UC is the only equation that includes the real characteristic length of the process (ρ_0). On the other hand, the standard boiling heat transfer experiment bypasses just the definition of this single parameter of heating surface influencing heat transfer.

In this connection, when processing the experimental data in the framework of the UC, it became necessary to characterize commercial heating surfaces on the basis of indirect estimates with a constant average value of ρ_0 [8]. For this reason, quite acceptable in itself, MRD of 10.8% can correspond to the UC only in the really unfeasible situation of the real constancy of ρ_0 of all experimental surfaces. Actually, of course, the numerous experimental surfaces deviated from the accepted value. As a result, in the still hypothetical situation, when the value of ρ_0 is known for each surface, the accuracy of the UC-based generalization can be noticeably higher. As shown in [46], in such a case, MRD can decrease almost two times.

More details about prolonged absurd situation with the characteristic length of boiling heat transfer, in general, are elucidated in [46]. At the same time, an important outcome of [46] is the first independent confirmation of the fundamental nature of the MTD-UC.

The conclusions drawn on the basis of the results of [43] are substantially strengthened by the results of the studies [44] devoted to the generalization of extensive experimental data on flow boiling. An experimental HTC database containing 2783 data points built from 26 open literatures for annular flow is covered. The database includes both macrochannel and mini-/microchannel data and covers wide range of working conditions. The annular flow database consists of seven working fluids, covering hydraulic diameters of 0.5–14.0 mm, mass velocities of 50–1290 kg/m^2 s, liquid-only Reynolds numbers of 240–55, 119, vapor qualities of 0.10–0.98, and reduced pressures from 0.01 to 0.77. In addition, 19 existing prediction methods for flow boiling are compared.

Really, the results of generalization of the experimental data showed fundamental characters of the MTD-UC and versatility of the UC, which outperformed in accuracy all the competitive equations. However, due to some sad missteps, very important work did not end with the adequate conclusions.

A critical mistake was the removal of the UC from the list of competing equations with subsequent exclusion from the published text of the UC-based generalization of the experimental data (necessarily preceding the obtaining of the UC-based so-called novel correlation). This step fundamentally contradicts the very logic of the MTD-UC, which reasonably claims to cover all classes of developed boiling heat transfer processes (see, for example, **Figure 8**).

As followed from the relevant analysis, the novel correlation [46] can hardly be regarded as a new result. It differs from the UC by two corrections of the opposite sign, each of which is noticeably smaller than the scatter of the experimental data (details of the examination are available in the “letter to the editor,” submitted to Applied Thermal Engineering).

In any case, we are dealing with the fact that the correlation, ignored for 50 years, in 2017 wins in a wide competition for the best description of the channel flow boiling heat transfer.

Ultimately, independent confirmation of the successful competition of the UC with two different groups of equations in describing the two main classes of processes of boiling heat transfer certainly gives it a special status. In addition, if remembering the correlation by the UC and the experimental data on boiling heat transfer of liquid metals and highly different liquids (water, refrigerants, and sodium) on the surfaces with known different values of the ER, the UC will generally remain beyond any competition.

4. Concluding remarks

In the final part, there always is a desire, together with the conclusions, to talk about plans for the future. However, in this particular case, because of historical reasons, the accumulated problems are so vast that their representation would take a lot of space. Therefore, in this context, we recommend the reader to get acquainted with the publications of recent years [45, 46], where the tasks for the future are described in sufficient detail.

The real picture of boiling heat transfer research is rather gloomy. Half a century of total ignoring of the boiling fundamentals could not but lead to logical consequences. Tens and even hundreds of thousands of scientific publications, numerous editions, and conferences exist by themselves. In rare cases, when the accumulated knowledge should explain the reality in the form of experimental databases, the terms physical model, theory, numerical model, criteria, cooling mechanism, characteristic length completely disappear, and "calculation methods" come to the fore, the pure empiricism represented in dimensionless form.

Excessive tightening makes the recognition process increasingly painful. First, it turns out that the scientist, who established the key role of transient conduction and microcirculation, does not know that this is just the PEGB. Then others establish an excellent description of flow boiling heat transfer by the UC and by making minor corrections of the opposite sign transform the fundamental result of 1960s into the "novel correlation." The third and fourth forget to add to the examined databases the experimental data on heat transfer during boiling of liquid metals, generally leaving the UC out of competition. Developers of highly efficient boiling surfaces forget to indicate the basics of the success.

The author's systematic calls for a broad discussion on the problem remain unproductive for decades. Heat transfer research community still cannot gain will and carry out targeted actions to rid of the heavy burden of the past. The problem goes beyond the scope of the particular scientific discipline.

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